Luminaire Luminance Uniformity
Implications of LLU

Diagram adapted from FINELITE

- Luminaire luminance uniformity
- Luminous efficacy
- Discomfort glare
- Visual appeal

Optical material properties

- Spacing between LEDs
- Luminous intensity
- Distribution of LEDs
- LED shape
- Chromaticity

Viewing distance and angle

Distance
Transmittance*: 89%  73%  64%

Sources: Whiteoptics
* Values from Itooptics library


Uniformity Metrics

- Max:Min
- Avg:Min
- Coefficient of variation (CV)
- Entropy Uniformity (EU)

\[ P_i = \frac{L_i}{\sum_{i=1}^{n} L_i} \]

\[ EU = \frac{1}{n} \cdot \exp\left(- \sum p_i \ln(p_i)\right). \]
Uniformity based on the Human Visual System (UHVS)

\[ U_{HVS} = \frac{1}{1 + k \cdot CV^\alpha \cdot NU_{HVS}^\beta} \]

- \( U_{HVS} \) ranges from 0 to 1
- Higher is more uniform

- Accounts for:
  - CSF of pattern
  - Adaptation luminance (cd/m\(^2\))
  - Viewing distance (m)
  - Pattern area (squared degrees)
  - Viewing angle (degrees)

**Performance of Metrics**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Adjusted $R^2$ (Yao et al. 2017)</th>
<th>$R^2$ (Abboushi et al. 2020)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max:Min</td>
<td>-</td>
<td>0.88</td>
</tr>
<tr>
<td>Avg:Min</td>
<td>0.71</td>
<td>0.50</td>
</tr>
<tr>
<td>Coefficient of variation (CV)</td>
<td>0.85</td>
<td>0.57</td>
</tr>
<tr>
<td>Entropy Uniformity (EU)</td>
<td>0.95</td>
<td>0.37</td>
</tr>
<tr>
<td>$U_{HVS}$</td>
<td>0.96</td>
<td>0.94</td>
</tr>
</tbody>
</table>


Procedure:
Luminance Measurements using High Dynamic Range Images

Eduardo Rodriguez-Feo Bermudez
Measuring Uniformity Using the LLUA

- Headless Raspberry Pi
- Debian/Linux
- Python 3
- Main Packages
  - Gtk3+
  - gphoto2
  - libusb
  - pyenttec
  - Phidget22
Phase 1 – Set up

• Set up the experimental space
  ▪ Darken the experimental space (i.e., turn off lights, close windows, etc.)
  ▪ Set the temperature to stable value
Phase 1 – Set up

- Set up the experimental space
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- Assemble the components of the LLUA
  - Add the high-definition camera
  - Add the luminance meter
  - Place the optical material to be tested in the slot the optical material slot
Phase 1 – Set up

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- Assemble the components of the LLUA
  - Add the high-definition camera
  - Add the luminance meter
  - Place the optical material to be tested in the slot
- Turn on the LED array at 100%
  - Measure the intensity output of the LED array every 5 minutes
  - Continue this process until the LED have reached stable conditions
Camera and luminance meter on the gimbal system

LED Array

Calibration plate
Phase 2 – Calibration

- Adjust distance
  - Set the distance between the optical material and the LED array
  - Set the distance between the two halves of the LLUA
Phase 2 – Calibration

- Adjust distance
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- Center the high-definition camera
  - Place the calibration in front of the optical material
  - Zoom and focus on the calibration plate until the numbers and scales are clearly defined
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• Center gimbal to the luminance meter
  ▪ Take note of the spot measurement location on the optical material
  ▪ Take luminance measurement value
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• Center the high-definition camera
  ▪ Place the calibration in and
  ▪ Capture pictures of the optical material at varying shutter speeds
Phase 3 – Automated Measurements

- Center the high-definition camera
  - Capture HDR of the optical material by taking pictures at varying shutter speeds from 6 seconds to 1/1600 seconds
• Center the high-definition camera
  ▪ Capture HDR of the optical material by taking pictures at varying shutter speeds from 8 seconds to 1/3200 seconds

Phase 3 – Automated Measurements
Phase 3 – Automated Measurements

- Move the LED array
  - Motors attached to the LED array move it back by desired increment
  - Capture pictures of the optical material at varying shutter speeds from 8 seconds to 1/3200 seconds
  - Center the luminance meter on the gimbal and take reference luminance spot measurement
  - Move back the LED array by desired increment and take luminance value
  - Center the camera and take HDR
  - Repeat for all desired distance between the LED array and optical
Combine pictures
Data Analysis and Results
Data Analysis Procedure

• Combine LDR images using radiance-based software, $raw2hdr^1$
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• Convert RGB values to luminance
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[Image of calibration pattern]
Data Analysis Procedure

• Combine LDR images using radiance-based software, raw2hdr\(^1\)
• Convert RGB values to luminance
• Calibrate image using calibration image and spot luminance measurement
• Calculate uniformity metrics
Material 1 Luminance Maps

- Scale: Luminance [cd/m^2]
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- Scale: Luminance [cd/m^2]
Material 1: LED Distance Extremes

LED Dist: 0.5 inches

LED Dist: 2.5 inches
Material 2 Luminance Maps

- Scale: Luminance [cd/m^2]
Material 2 Luminance Maps

- Scale: Luminance [cd/m^2]
Material 2: LED Distance Extremes

LED Dist: 0.5 inches

LED Dist: 2.5 inches
Uniformity Metrics: Max/Min

Max/Min across LED Distance

Material 1

Material 2
Uniformity Metrics: Avg/Min
Uniformity Metrics

- CV across LED Distance
- EU across LED Distance
- Uhvs across LED Distance
Conclusions

• The luminance uniformity of a luminaire aperture can have implications for:
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• The uniformity of luminance distributions can be quantified by evaluating HDR images

• Future work
  ▪ Examine the performance of uniformity metrics in relation to subjective ratings
  ▪ Develop a stray light correction matrix for further accuracy
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